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Determination of the Strong Coupling Constant in Jet Production at HERA

Tancredi Carli[1]

[1] Max Planck Institut für Physik
E-mail: Tancredi.Carli@desy.de
On behalf of the H1 and ZEUS Collaborations.

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Abstract

Recent α_s determinations from jet production at HERA are presented. Three different observables lead to consistent α_s values. The most accurate result is: $\alpha_s(M_Z) = 0.1181 \pm 0.0030\ (\text{exp.})^{+0.0039}_{-0.0046}\ (\text{theo.})^{+0.0036}_{-0.0015}\ (\text{pdf})$.

1. Introduction

Perturbative Quantum Chromodynamics (pQCD), the theory describing short distance strong interactions, has a single free parameter, the strong coupling constant α_s. This coupling depends on the renormalisation scheme and the energy scale. At the reference scale, which is customarily chosen as the mass of the Z^0 boson, the strong coupling is presently known to an accuracy of about 4% [1]. This is more than a factor of 10 less precise than the coupling of the weak force. Measurements of α_s over a wide energy range provide a fundamental test of the evolution predicted by the QCD β-function and can severely constrain physics beyond the Standard Model.

Precise determinations of α_s have been performed in e^+e^- annihilation processes over a large range of centre of mass energies from $14 < \sqrt{s} < 189$ GeV using jet rates, event shapes, τ decays and the inclusive ratio of hadron to lepton branchings [1].

Jet production at hadron colliders is a particularly well suited process to measure the energy dependence of α_s in one single experiment. However, the presence of hadrons in the initial state leads to the complication that the measured cross section always depends on the product of α_s and the parton density functions (PDF).

The high centre of mass energy (s) of HERA, colliding 27.5 GeV positrons on 820 GeV protons, allows hard processes to be studied in deep-inelastic scattering (DIS). Particularly well suited for pQCD studies is the Breit frame in which the photon is purely space-like and collides head-on with the proton. Besides the photon virtuality, Q^2, the transverse energy E_T produced in the Breit frame provides a hard scale.

Jet cross sections at high E_T are collinear and infrared safe observables which can be calculated in pQCD.

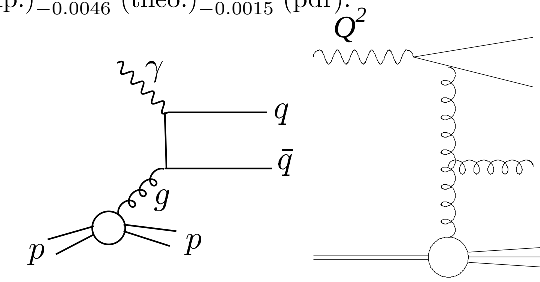

Figure 1. *Examples of $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_s^2)$ Feynman diagrams dijet events in $e^{\pm}p$ -collisions.*

The jet cross section σ_{jet} can be expanded to:

$$\sum_{a,n} \alpha_s^n(\mu_r^2) \int_0^1 \frac{d\xi}{\xi}\, C_{a,n}(x_{Bj}/\xi, \mu_r^2, \mu_f^2, ...) f_{a/p}(\xi, \mu_f^2),$$

where $x_{Bj} = Q^2/(2p \cdot \gamma)$, $\xi = x_{Bj}\ (1 + M_{j,j}^2/Q^2)$ is in leading order (LO) the fractional momentum of the struck parton in the proton and $M_{j,j}$ the invariant dijet mass. μ_r (μ_f) is the renormalisation (factorisation) scale. The perturbatively calculable coefficients $C_{a,n}$ are presently known to next-to-leading order (NLO). The jet cross section is directly sensitive to α_s and the gluon ($f_{g/p}$) and quark ($f_{q/p}$) densities in the proton. For low Q^2 (below ≈ 40 GeV^2) jet cross sections calculated in NLO strongly depend on μ_r [2, 3]. pQCD analyses are therefore better performed at high Q^2, where also hadronisation effects are smaller [3].

Double differential inclusive dijet cross sections $d^2\sigma/d\xi dQ^2$ and $d^2\sigma/dxdQ^2$ for $200 < Q^2 < 5000$ GeV^2, where jets are defined by the inclusive K_T algorithm [4] asking for $E_T > 5$ GeV , $E_{T,1} + E_{T,2} > 17$ GeV and $-1 < \eta_{lab} < 2.5$ have been used for a preliminary extraction of the gluon density in the range $0.01 \leq \xi \leq 0.1$ at fixed $\mu_f^2 = 200$ GeV^2 [5]. In this analysis α_s has been set to

† The pseudo-rapidity is defined by $\eta = \ln \tan\theta/2$.

the world average. F_2 data [6] for $200 < Q^2 < 650$ GeV^2 have been included in a combined fit to get an additional constraint on the quark densities.

At this conference new preliminary results have been presented where the opposite strategy has been pursued. The parton densities have been taken from global fits to inclusive DIS data and exclusive high-E_T processes and then α_s is fitted. Either sets of PDF with different input α_s have been used to account for the anti-correlation between α_s and the PDF or the dependence on the PDF is included in the systematic error. The final aim is to perform a consistent simultaneous fit of both α_s and the PDF.

2. α_s from Inclusive Jet Cross Sections

The single inclusive jet cross section $d\sigma/dQ^2dE_T$ has been measured in four different Q^2 regions within $150 < Q^2 < 5000$ GeV^2 and $0.2 < y = Q^2/(s\ x_{Bj}) < 0.6$ by the H1 collaboration. Jets are defined by the inclusive K_T algorithm requiring $E_T > 5$ GeV in the range $-1 < \eta_{lab} < 2.5$. The data are corrected for detector effects. Over the whole phase space reaching E_T up to 50 GeV a NLO calculation based on DISENT [7] using the CTEQ5M [8] PDF with $\mu_r^2 = E_T^2$ and $\mu_f^2 = 200$ GeV^2 describes the data. Hadronisation effects lower the NLO prediction by about $3-10\%$ [3]. For each E_T and Q^2 bin α_s is adjusted to the measured cross section using a χ^2 minimisation where the systematic errors are included in the fit [9]. All results are consistent with each other. In Fig. 2 the results are shown as a function of E_T after having combined the four Q^2 bins. The fitted α_s evolve as predicted by the renormalisation group equation. The combined $\alpha_s(M_Z^2)$ result is:

$$0.1181 \pm 0.0030\ (\text{exp.})\ ^{+0.0039}_{-0.0046}\ (\text{theo.})\ ^{+0.0036}_{-0.0015}\ (\text{pdf.})$$

The largest contribution to the experimental error comes from the uncertainty on the hadronic energy scale. The theoretical error is mainly determined by the uncertainty of the hadronisation corrections and by the μ_r dependence. The contribution obtained by varying μ_r^2 by a factor of 4 amounts to $^{+0.0025}_{-0.0034}$. The hadronisation uncertainties are estimated in a very conservative way using the QCD Monte Carlo models. Since the spread between this models is rather small, half of the size of the hadronisation corrections, but at least 3%, is assigned as systematic uncertainty. If $\mu_r^2 = Q^2$ instead of $\mu_r^2 = E_T^2$ is used a consistent $\alpha_s(M_Z^2)$ result is obtained:

$$0.1221 \pm 0.0034\ (\text{exp.})\ ^{+0.0054}_{-0.0059}\ (\text{theo.})\ ^{+0.0033}_{-0.0016}\ (\text{pdf})$$

For $\mu_r^2 = Q^2$ the μ_r dependence increases by $\approx 40\%$.

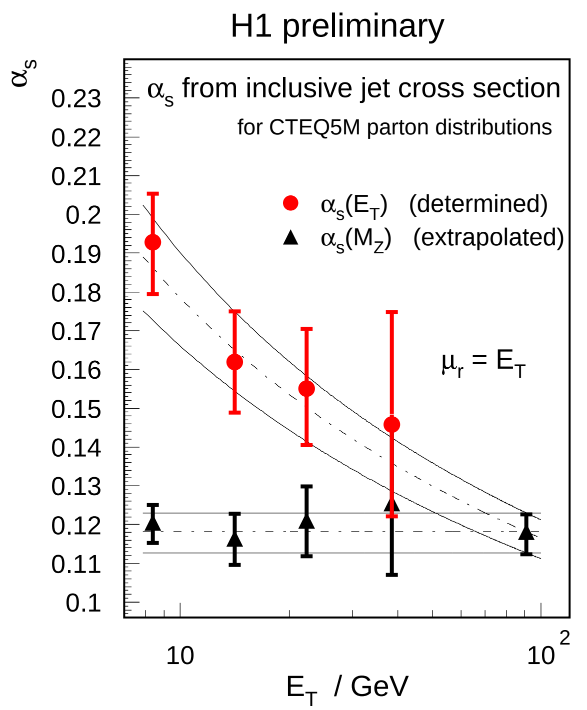

Figure 2. *α_s fit result versus the jet E_T. The lines indicate the prediction of the renormalisation group equation for the combined results and their uncertainty.*

The systematic uncertainty on the PDF is difficult to estimate, because none of the global analyses has yet provided PDF errors. Since the fit results of the different groups, MRST [10] and CTEQ [8], are based on similar data sets and assumptions, the spread of different parametrisation does not give a realistic error evaluation. Recently the CTEQ collaboration [11] has investigated possible variations on the gluon distribution using different parametrisations and allowing the quality of the fit to be degraded. The resulting parametrisation is the first step towards the estimation of uncertainties, but can not replace a proper error analysis.

Another point of concern is the influence of the α_s value used when deriving the PDF. If a strong correlation between the fit result and the initial assumption on α_s was found, it would be questionable whether the ansatz to fix the PDF and to extract α_s would be meaningful. This dependence can be tested by means of series of parton distributions scanning from low to high values of α_s.

A comprehensive study of the fitted α_s on all available recent PDF, is presented in Fig. 3. The largest deviation to the central result obtained with the CTEQ5M parametrisation is quoted as

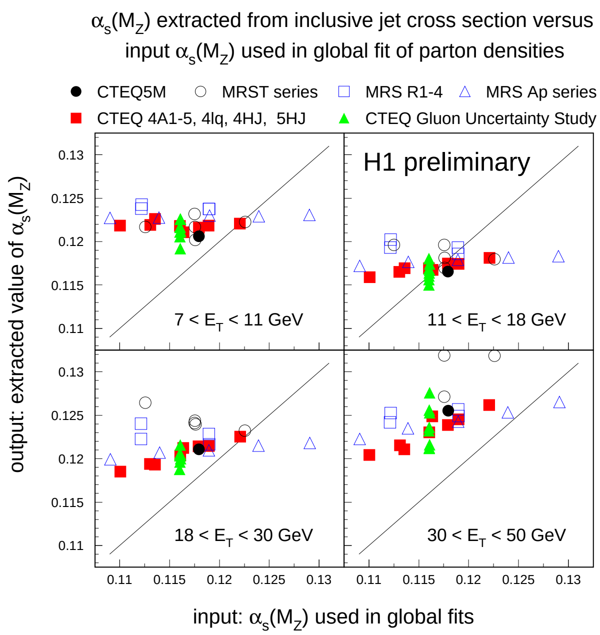

Figure 3. *Dependence of the α_s fit results on the assumed PDF in four E_T regions.*

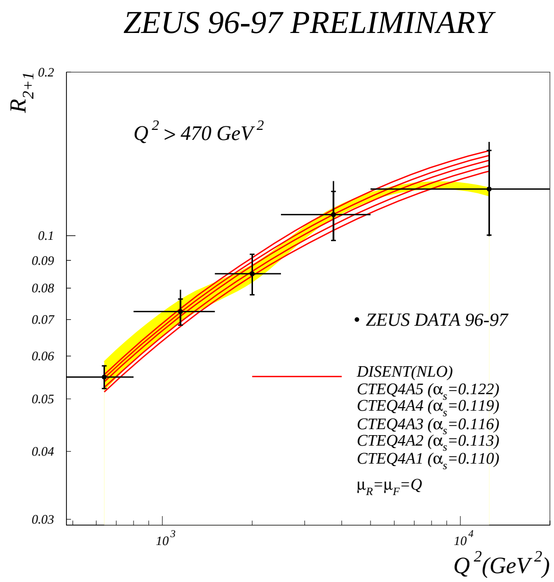

Figure 4. *Exclusive dijet rate as a function of Q^2.*

systematic error. Only for the highest E_T a slight dependence on the $\alpha_s(M_Z^2)$ value used in the global fits is found. For all other bins no correlation is observed. This is different from the observation made by the CDF collaboration [12] in an analysis of single inclusive jet cross sections measured in $p\bar{p}$ collisions where a strong correlation between the α_s used in the PDF and the fit result was found.

3. α_s from Dijet Rates

The ZEUS collaboration has measured dijet cross sections and rates in the phase space $470 < Q^2 < 20000$ GeV^2 and $0 < y < 1$. Jets are defined as in the dijet analysis described before, except that the two highest E_T (and not all) jets have to fulfil $-1 < \eta_{lab} < 2$. In addition, only events with exactly two jets are considered. The exclusive dijet cross sections as a function of E_T, $M_{j,j}$, η_{lab}, x_{Bj} , $z_{p,1} = E_1\,(1-\cos\theta_i)/(\sum_{k=1,2} E_k(1-\cos\theta_k))$, and ξ are - both in shape and in absolute magnitude - well described by a NLO calculation using CTEQ4M [13] for $\mu_r^2 = \mu_f^2 = Q^2$. The data are corrected for detector, electroweak radiation and hadronisation effects. Hadronisations corrections are at most 10% and decrease with increasing Q^2. For $Q^2 > 5000$ GeV^2 the contributions from Z^0 exchange become visible. They have been subtracted from the data.

The good description of the data allows an extraction of α_s from $R_{2+1}(Q^2) = \sigma_{2+1}(Q^2)/\sigma_{\rm tot}(Q^2)$.

The dijet rates shown in Fig. 4 are compared to NLO QCD calculations based on the CTEQ4A PDF series which have been fitted for different α_s assumptions. This series is also used to parametrise the anti-correlation between α_s and the PDF [14]. The value of α_s is obtained from a χ^2 minimisation:

$$0.120 \pm 0.003\ ({\rm stat.})\ ^{+0.005}_{-0.006}\ ({\rm exp.})\ ^{+0.003}_{-0.002}\ ({\rm theo.})$$

The experimental systematic error is dominated by the uncertainty on the hadronic energy scale (±0.005). QCD Model dependencies to unfold the data to parton level account for an error of $^{+0.001}_{-0.002}$. The theoretical uncertainty is estimated by varying the renormalisation scale $\mu_r^2 = Q^2$ by a factor of 2 (±0.002), by replacing the assumed PDF by MRST sets (-0.002) and by taking DISASTER++ [15] instead of DISENT (±0.002). If μ_r^2 is varied by a factor of 4 as in the previous analysis, the μ_r uncertainty increases to ±0.004. The dijet rates change only by at most 2.5% when the PDF from the CTEQ gluon uncertainty study is used. The influence on the α_s result is therefore expected to be small.

4. α_s from Differential Jet Rates

H1 has measured $1/N_{tot}\,(dn/dQ^2dy_2)$ for $Q^2 > 150$ GeV^2 and $0.1 < y < 0.7$. All particles are clustered on the basis of a distance measure $y = d_{i,j}/$scale, where $d_{i,j} = 2\min{(E_i^2, E_j^2)}(1-\cos\theta_{i,j})$, until $2+1$ jets are found . y_2 is the smallest value

† +1 denotes the proton remnant. E_i is the energy of the particles and $\theta_{i,j}$ the angle between them.

of y where two jets can be resolved. It is therefore a measure for the jet structure. Two jet algorithms are used. In both cases the data are described by a NLO calculation based on CTEQ5M [17].

The K_T jet algorithm for DIS [16] is applied in the Breit frame and scale is set to 100 GeV^2. The proton remnant p is included as particle with $d_{i,p} = 2E_i^2(1 - \cos\theta_i)$. After a cut $y_2 > 0.8$ only events with $E_T > 10$ GeV in the Breit frame remain. A χ^2 minimisation gives $\alpha_s(M_Z^2)$:

$$0.1143\ {}^{+0.0075}_{-0.0089}\ (\mathrm{exp.})\ {}^{+0.0074}_{-0.0064}\ (\mathrm{theo.})\ {}^{+0.0008}_{-0.0054}\ (\mathrm{pdf})$$

A variant of the JADE algorithm is applied in the HERA laboratory frame and the squared invariant mass of the hadronic final state W^2 is used as scale, applied in the HERA laboratory ("mod. Durham algorithm"). A massless particle is added in the clustering procedure to account for the escaped longitudinal momentum. y_2 is required to be above 0.005 to select hard processes. The fit result is:

$$0.1189\ {}^{+0.0064}_{-0.0081}\ (\mathrm{exp.})\ {}^{+0.0059}_{-0.0046}\ (\mathrm{theo.})\ {}^{+0.0013}_{-0.0055}\ (\mathrm{pdf})$$

The quoted values are obtained for $Q^2 > 575$ GeV^2, the lower Q^2 regions give consistent results. The experimental errors are dominated by the energy scale uncertainty and by the QCD model dependence of the detector correction. The theoretical uncertainty is given by the hadronisation correction (± 0.0026) and the μ_r dependence: ${}^{+0.0053}_{-0.0038}$ for $\mu_r^2 = Q^2$ and ${}^{+0.0025}_{-0.0007}$ for $\mu_r^2 = E_T^2$. The correlation between the fitted α_s and the value assumed in the PDF seems to be - in particular at low Q^2 - stronger for jet rates than for jet cross sections.

5. Summary

$\alpha_s(M_Z)$ has been determined in NLO from jet observables in DIS at HERA (see Fig. 5). The result is consistent with the world average and has an error of about 0.006. This is quite a remarkable result, since it is only slightly less precise than the world average value having an error of 0.004 [1].

In future, fitting technique using F_2 and jet data should be further developed to allow a simultaneous fit of α_s and the PDF from HERA data alone.

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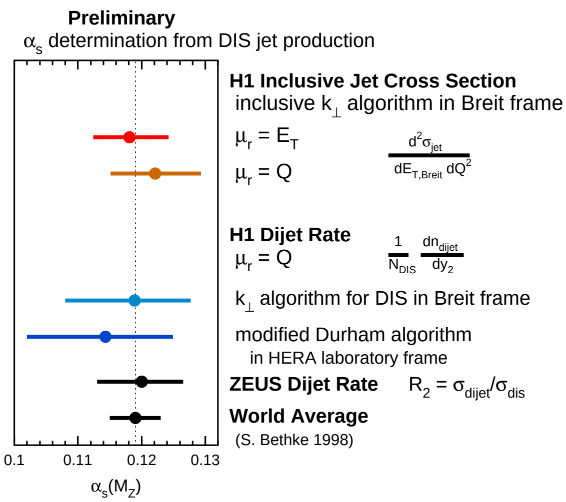

Figure 5. *Summary of recent α_s results from jets.*

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